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Impact Dynamics of the M557 Fuze

by G. A. Gazonas

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G. A. Gazonas
Weapons and Materials Research Directorate, ARL

Abstract

This report outlines the results of a combined experimental and computational study that investigates the transient structural response of the M557 point detonating fuze subjected to low-speed (200 m/s) oblique impact by a hardened-steel projectile. The problem is of interest to the explosive ordnance disposal (EOD) community as it is a method that is currently used to "render-safe" ordnance and other explosive devices found in the field. An inert M557 fuze is instrumented with a low-mass (1.5 gram) 60-kilo-g uniaxial accelerometer and subjected to oblique impact by launching a 300-gram projectile from a 4-in airgun. The transient structural response of the fuze is compared to the predicted response using the Lagrangian finite element code DYNA3D. Peak accelerations measured in two tests average 35 kilo-g, whereas DYNA3D predicts a 40- to 50-kilo-g peak acceleration depending upon the amount of prescribed damping. Both measured and computed acceleration histories are Fourier-transformed, and the estimated spectral response at the base of the fuze is shown to be dependent upon the failure strength of the flash tube.

Acknowledgments

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1. Introduction

The explosive ordnance disposal (EOD) community utilizes a variety of devices to disarm or "render-safe" ordnance and other explosive devices found in the field [1]. One class of render-safe methods can be termed "mechanical" in that it relies on a measured use of mechanical force to sever or disrupt the explosive initiation train within the fuze. In this study, the Navy EOD customer was interested in assessing the predictive capabilities of a Lagrangian-based hydrocode in modeling the oblique impact and penetration of the M557 fuze by a hardened-steel projectile.

The work focused on investigating the "structural" damage (i.e., the mechanical response) imparted to an inert fuze as a result of an oblique impact, rather than establishing the impact conditions necessary to render-safe an actual fuze device. A typical fuze geometry consists of a right-circular cone that threads into the ordnance at its base (Figure 1). The cutaway view also illustrates some of the important internal fuze components such as the firing pin, detonator and booster. Although these components are critical for proper operation of the fuze under normal impact conditions, replacing the "fine" internal structure of the fuze with a homogeneous core material simplified modeling the oblique impact problem.

The fuze selected for analysis was the M557 point detonating fuze comprised of a thin-walled mild-steel (1006) ogive that houses a threaded mild-steel base and flash tube. The firing pin, safety spring, detonator, and other intricate nose-cone components were modeled with a homogeneous 6061-T6 aluminum nose cone. The solid, 300-gram cylindrical projectile consisted of hardened Rc-57 steel, 1 in in diameter and 3 in in length. The projectile is designed to strike the fuze normal to its axis of symmetry during render-safe procedures (Figure 2).

The explicit Lagrangian hydrocode DYNA3D (the 1994 version) [2, 3] was used to simulate the transient impact event since this code has been successfully employed to model other highly transient, physical phenomena [4]. In order to quantitatively assess the predictive capabilities of

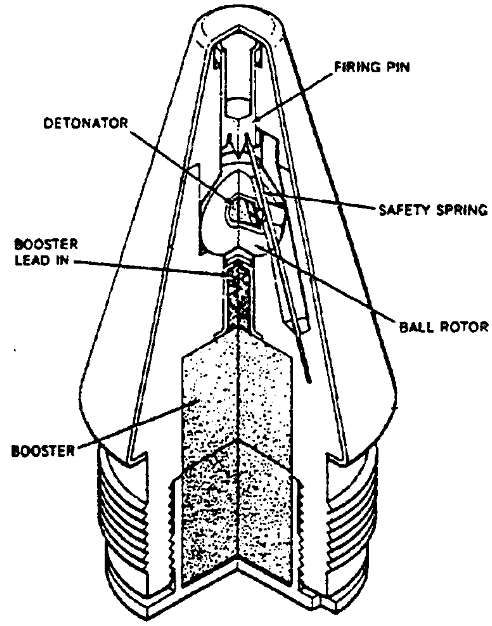

Figure 1. Cutaway View of a Typical Fuze Illustrating Internal Components.

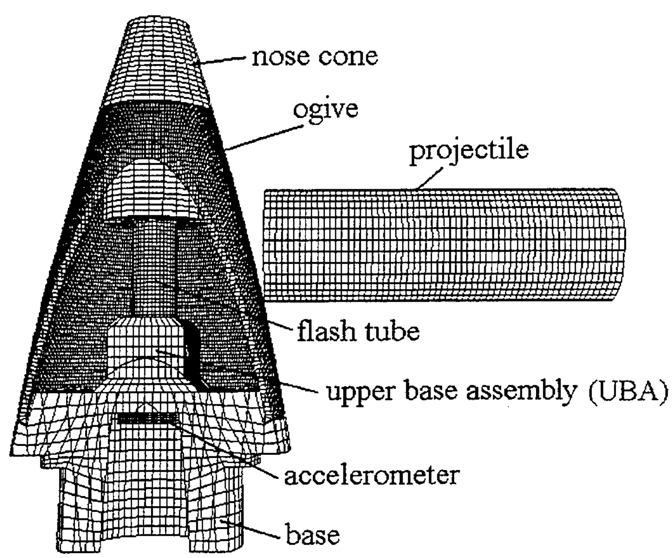

Figure 2. Cutaway View of the Finite Element Model Illustrating the Geometry and Grid of Elements of the Fuze and Projectile.

the hydrocode, the fuze was instrumented with a lightweight 60 kilo-g uniaxial accelerometer and subjected to oblique impact by launching a 300-gram projectile at constant velocity (200 m/s) from a 4-in airgun. Acceleration histories recorded by the accelerometer mounted on the base of the fuze were compared to the accelerations predicted by DYNA3D. The accelerometer was modeled as a small, rectangular, lightweight mass attached to the base of the fuze.

The results of two oblique fuze impact tests revealed that peak accelerations at the base of the fuze averaged 35 kilo-g, while the predicted peak accelerations ranged from 40 to 50 kilo-g depending upon the amount of prescribed damping. The measured acceleration histories were highly variable in the time domain, so the signals were Fourier-transformed to determine how well the frequency content of the impact event compared with the frequencies of the predicted response using DYNA3D. The measured accelerations contained a dominant energy peak near 30 kHz, whereas the computational results revealed the presence of an energy peak at 30 kHz and another at 120 kHz. The predicted temporal and spectral responses recorded at the base of the fuze strongly depended upon the failure strength of the flash tube.

2. DYNA3D Computations

Computations were performed using the explicit Lagrangian hydrocode, DYNA3D, developed by the Lawrence Livermore National Laboratory (LLNL) in 1977. The code is in use by the aircraft industry (Boeing) and the automobile industry (Volvo, Saab, General Motors, and Japanese manufacturers) for crash and safety modeling and has seen continuous development and use since its initial introduction. The finite element computational grid consists of 76,970 nodes and 53,516 hexahedral finite elements (Figure 2). The ogive consists of three hexahedral elements through the thickness. Computations proceeded through three phases: pre-processor, main cycle, and post-processor, corresponding to PATRAN, DYNA3D, and TAURUS routines, respectively. The rate and temperature-dependent Johnson-Cook model simulated the constitutive behavior of the 1006 mild steel and 6061-T6 materials. The accelerometer behavior was linear elastic. Fixing the outer surface coordinates of the fuze base simulated the experimental test condition, whereby the fuze base was threaded into a massive steel plate to

prevent motion during impact. Nonreflecting boundary conditions were also assigned to the nodes on this surface. The flash tube is threaded into the upper base assembly (UBA) (Figure 2), which contains internal structure not included in the finite element model. To simulate stress wave attenuation in the UBA, the global-damping feature available in DYNA3D (Rayleigh damping extended to nonlinear analysis) was used with damping coefficients set at $\alpha = 0$, and $\beta = 10^{-8}$ [2]. The projectile strikes the fuze at an initial velocity of 200 m/s. The impact position was identical to that in the airgun tests described in section 3. Ten sliding interface definitions prevented interpenetration of the various colliding solids during impact. The simulation of penetration and fragmentation of the ogive employed the "slidesurfaces with adaptive new definitions" (SAND) algorithm. Ogive failure commenced when the equivalent plastic strain of a particular element in the ogive attains a value of $\bar{\varepsilon}^{p} = 0.30$. Flash-tube fracture was simulated using the "node spotwelded to surface" slideline feature in DYNA3D. The slideline releases nodes along a "failure" surface when a predefined level of the normal and shear failure strength of the flash tube is exceeded [2].

Computations were conducted on a 64-bit Cray C90 vector computer and terminated at 500 μs with a sampling rate of 2 μs/pt (500 kHz), corresponding to a Nyquist rate of 250 kHz. The computations cost an average of 0.1 central-processing-unit (CPU) hr/μs. The computed accelerations of various fuze components, such as the center of gravity (cg) of the accelerometer, were directly compared with measured accelerations. Some salient features of render-safe impact dynamics that depict the fuze deformation history appear in Figure 3. The gross features of ogive fragmentation and flash-tube failure were successfully simulated. However, some minor slideline interpenetration occurred between the base of the fuze and the ogive at 500 μs due to the complexity of the multiple slideline definitions. The projectile velocity vs. time plot (Figure 4) shows that projectile deceleration corresponds to impact into the ogive and nose cone/flash tube. Constant velocity portions of the curve represent periods of time when the projectile is essentially in "free flight." The projectile pierces through the thin-walled ogive at 45 μs and impacts the nose cone at 68 μs. At 104 μs, the projectile is in full contact with the flash tube. At 140 μs, the projectile severs the flash tube at its base and begins to severely

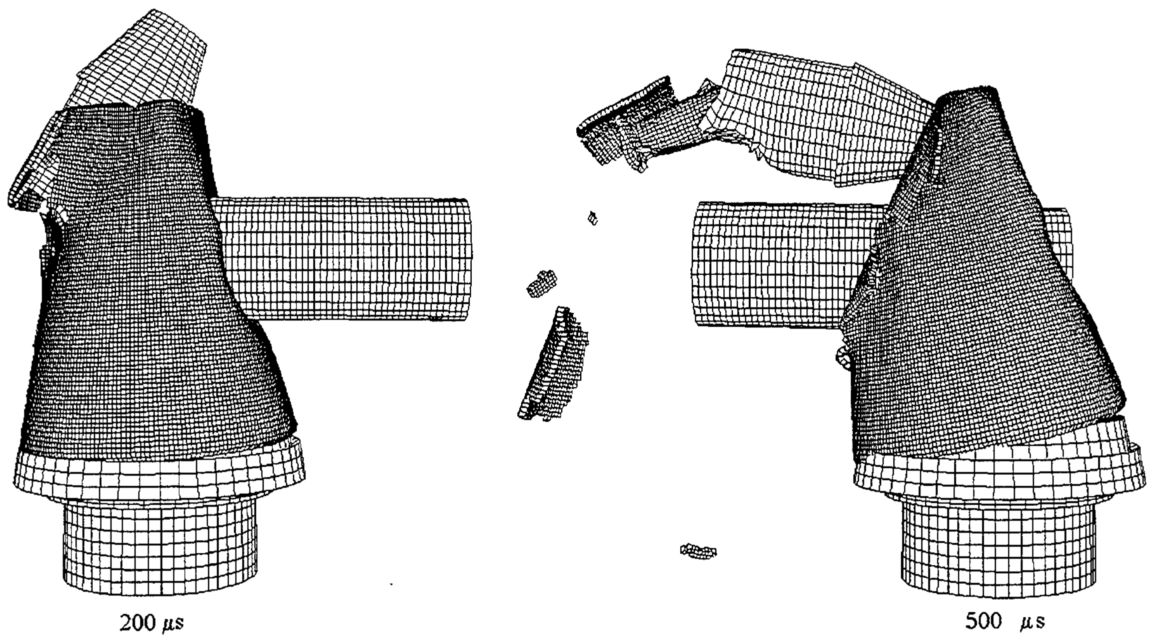

Figure 3. DYNA3D Simulation Results Showing Deformed Fuze and Ogive Fragmentation at 200 and 500 μs.

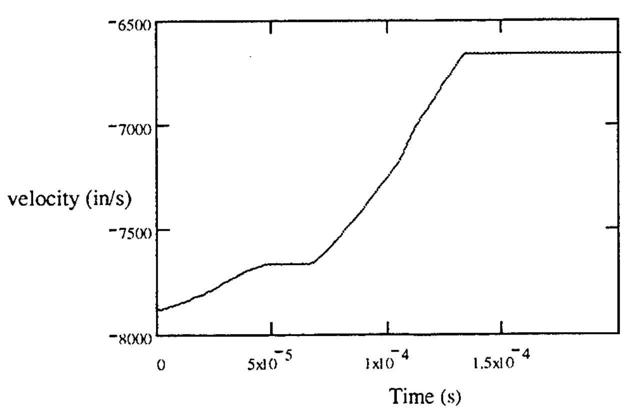

Figure 4. Velocity History of the Projectile cg.

deform the interior surface of the ogive. The projectile pierces completely through the ogive at 200 μs, and, at 500 μs, the nose cone and flash tube rotate up and out of the flight path of the projectile.

3. Airgun Experiments

Oblique fuze impact tests were conducted at an indoor airgun test range at Adelphi, MD. The test range includes a variety of airgun devices designed to gradually accelerate projectiles to ballistic velocities for high-g impact experiments. The airgun consists of eight 12-ft-long sections, connected in tandem to form a single gun tube 96 ft long, with a 4-in inner diameter. The projectile is loaded into the breech (right-hand side of Figure 5), after which the entire gun tube ahead of the projectile is evacuated to ~1 torr. The projectile is released and gradually accelerated toward the muzzle of the gun by atmospheric pressure acting on its base. The exit velocity of the projectile is determined with either a streak camera or a light-emitting diode system mounted near the barrel exit (Figure 6). Since the projectile diameter in these experiments is much less than the bore diameter of the airgun, a cylindrical bakelite carrier, 4 in in diameter, transports the projectile during flight down the gun tube. Several trial test shots establish the precise weight (projectile + carrier) necessary to achieve an exit velocity of 200 m/s. The projectile flies through a 2-in hole in a steel plate at muzzle exit, which strips off the bakelite carrier (Figure 6). During impact, the projectile pierces through the ogive and severs the flash tube near its base. New bakelite carriers were used for each test, as they shattered on impact with the steel plate.

A 1.5-gram 60-kilo-g uniaxial ENDEVCO Model 7270A-60K piezoresistive accelerometer was mounted on the base of the fuze just below the flash tube and within the cavity which normally contains explosive booster material (Figure 1). The vertical component of the acceleration vector at the base of the fuze was recorded. The 7270A accelerometer is a rugged undamped unit designed specifically for shock measurements. The mounted resonance frequency is 700 kHz, and a near-zero damping allows the accelerometer to respond accurately to fast rise-time, short- duration shock events. The accelerometer signal was conditioned using a Pacific Instruments signal conditioner (Model 8655). Using a signal generator to input a 10-kHz signal with a voltage range comparable to a shock amplitude ranging from 10 to 80 kilo-g, the maximum output voltage had a peak-to-peak amplitude error on the order of 5%. In addition, by maintaining constant voltage and stepping the input frequency in 10-kHz steps to 200 kHz, the

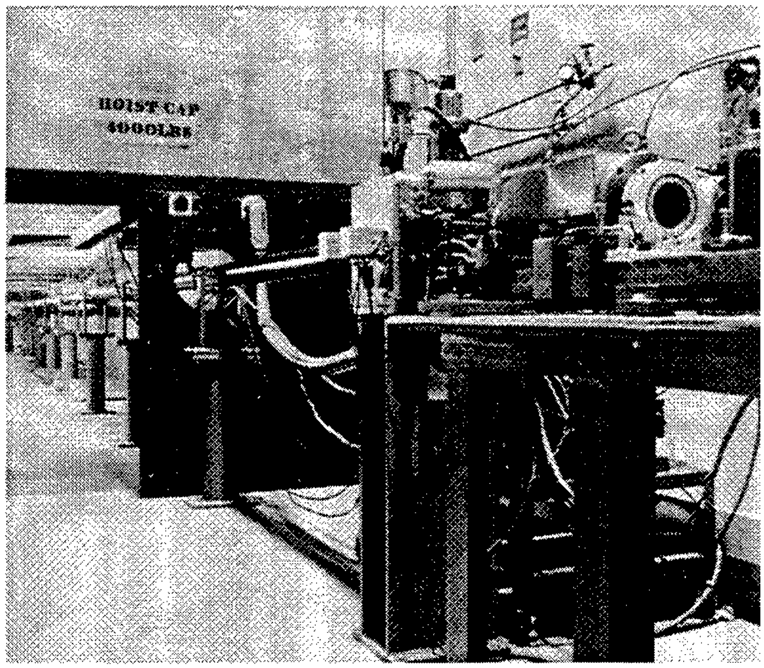

Figure 5. View of 4-in Airgun From Breech End.

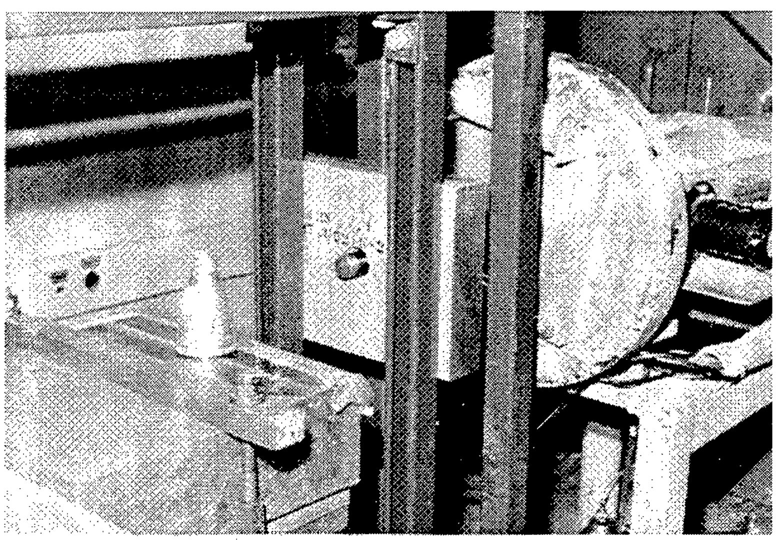

Figure 6. View of 4-in Airgun From Muzzle Showing M557 Fuze.

output voltage decreased by 0.82 dB at 100 kHz and 3 dB at 165 kHz. Data were sampled at a rate of 0.5 μs/pt (2 MHz), corresponding to a Nyquist rate of 1 MHz, and stored on a Nicolet 2090 oscilloscope for subsequent analysis.

4. Comparison of Airgun Test Results With DYNA3D Predictions

The acceleration history for shot no. 1 of two separate airgun tests is shown in Figure 7. The measured peak vertical accelerations were on the order of 35 kilo-g and decay rapidly with time. The variability in the observed acceleration histories highlights one difficulty associated with data acquisition in structures subjected to shock and impact. Consequently, the requirement for model validation in the time domain was relaxed by comparing the spectral characteristics (frequency domain) of the measured and predicted signals. To this end, the power spectral density of the acceleration history was estimated by computing the so-called periodogram [5], which is based upon computation of the fast Fourier transform (FFT) [6]. The computational economy of the FFT makes this approach one of the most popular methods for spectral estimation. Conventional FFT spectral estimation is based upon a Fourier series model of the data; that is, the process is assumed to be composed of a set of harmonically related sinusoids.

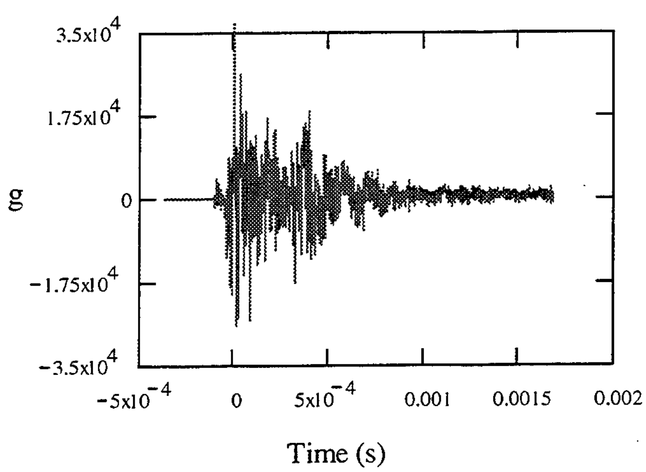

Figure 7. Accelerometer Response for Shot No. 1.

For this problem, this is not a bad assumption given the fundamental nature of wave propagation in media. FFTs of the measured accelerations were computed using the Mathcad 7.0 software package [7], and, from these transformations, periodograms were computed (Figure 8). The FFT of the vector v_k in Mathcad 7.0 is computed using,

$$c_j = \frac{1}{\sqrt{N}} \sum_{k=o}^{N-1} v_k e^{2\pi i (j/N)k}, \tag{1}$$

with corresponding frequencies,

$$f_k = \frac{k}{N} f_s, \tag{2}$$

which depend upon the sampling frequency f_s and the number of samples N. The periodogram plots were formed by squaring the magnitude of the vector in equation 1 (see e.g., Oppenheim and Schafer [8]) and revealed the presence of a dominant energy peak at 30 kHz that is undoubtedly related to some physical phenomenon associated with the impact event. The longitudinal wave speed, 146,316 in/s, in the accelerometer was estimated from its modulus and bulk density. Hence, the fundamental frequency of an acoustic wave traveling vertically through the 0.11-in-thick accelerometer was computed to be about 665 kHz. Thus, the relatively low frequency peak at 30 kHz is produced by some other mechanical disturbance, possibly due to the fracture failure of the flash tube. The discussion in a subsequent section examines this

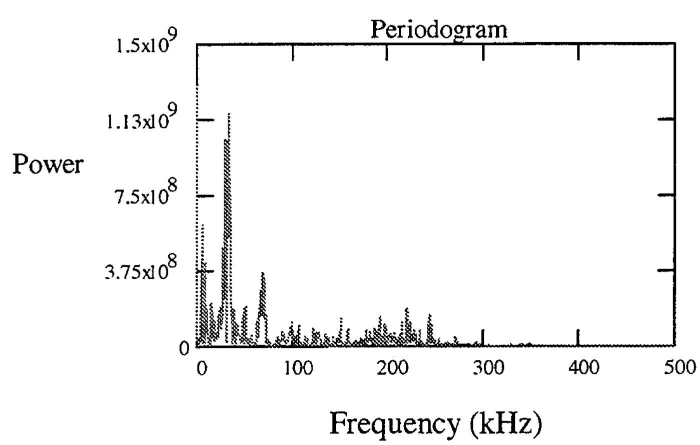

Figure 8. Periodogram for Shot No. 1.

Hypothesis. The same spectral estimation methodology was applied to the vertical accelerations computed for the cg of the modeled accelerometer in the DYNA3D analysis. The acceleration history for the DYNA3D analysis is shown in Figure 9. Comparison of the actual and simulated periodograms in Figures 8 and 10 reveals that the measured accelerations contain a dominant energy peak at 30 kHz, whereas the computational results predict an energy peak at 30 kHz and an additional energy peak at 120 kHz. Additional airgun tests and simulations were performed to gain a better understanding of the physical phenomenon causing the observed energy peak at 30 kHz and why DYNA3D predicts an energy peak at 120 kHz.

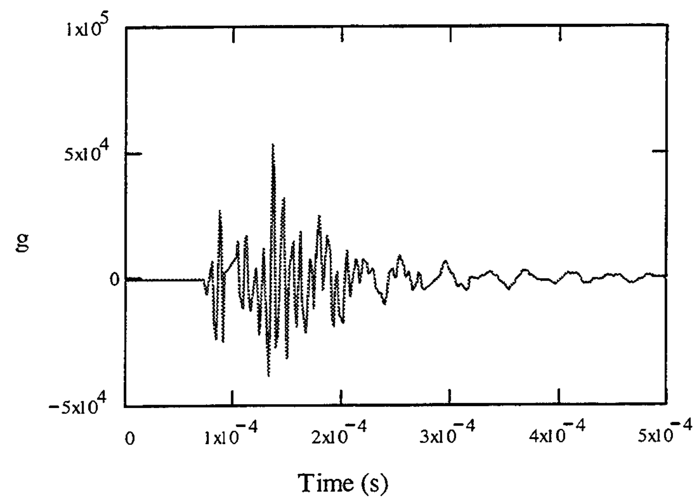

Figure 9. Simulated Accelerometer Response.

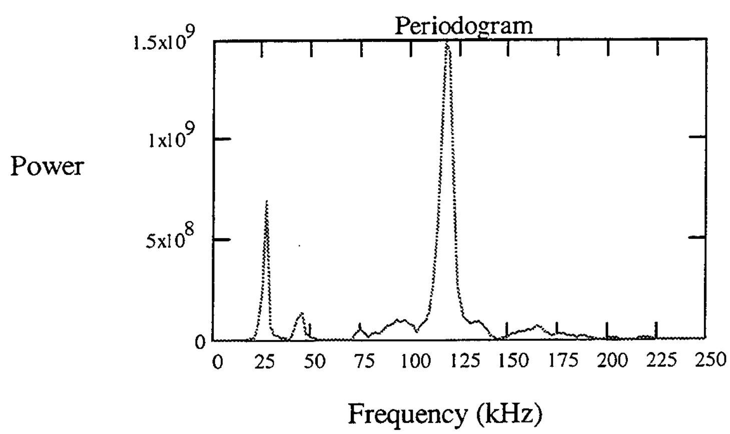

Figure 10. Periodogram for Simulated Response.

4.1 Additional Airgun Tests. Two additional airgun experiments were performed whereby the M557 fuze was replaced with a fuze "simulant" constructed from hot rolled steel. In addition, the simulant was further simplified by removing the ogive and nose cone, so that only the flash tube and base were subjected to impact. The impact and boundary conditions were identical to those in the previous airgun impact tests. The acceleration histories and periodograms for one test appear in Figures 11 and 12. Interestingly, the periodograms for the fuze simulant tests also reveal dominant energy peaks at 30 kHz and indicate that the ogive and nose-cone structural components do not appreciably contribute to the spectral response of the M557 fuze. Although

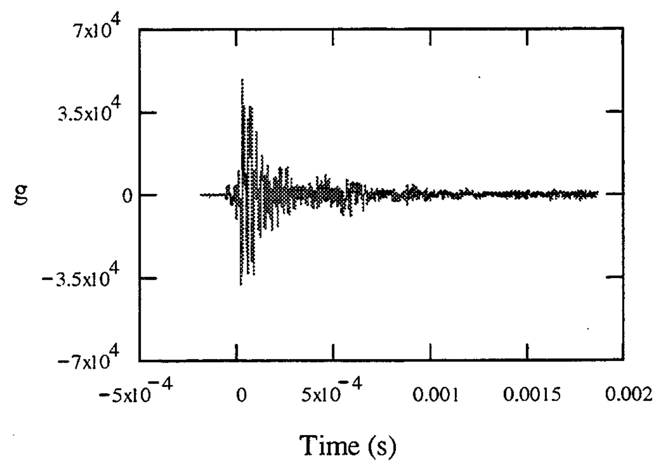

Figure 11. Accelerometer Response for Fuze Simulant.

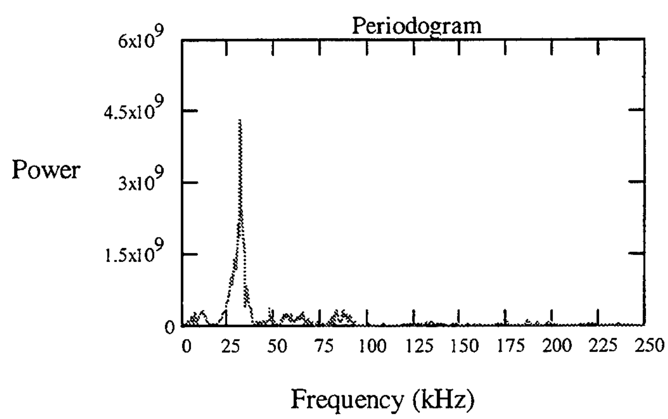

Figure 12. Periodogram for Fuze Simulant.

the projectile pierces through the ogive and impacts the nose cone during render-safe operations, these collisions do not measurably influence the spectral response of the M557 fuze.

4.2 Additional DYNA3D Simulations. Another parameter that can influence the measured spectral response is the failure strength of the flash tube. As described in section 2, flash-tube failure was modeled using the "node spotwelded to surface" slideline feature in DYNA3D. With this feature, nodes along a "failure" surface are released when a predefined level of the normal and shear failure strength of the flash tube is exceeded. The flash-tube failure strength was artificially modified by conducting two additional simulations whereby its strength is first decreased and then increased by an order of magnitude, from its nominal value in prior simulations. The acceleration histories and periodograms for the "weak," "nominal," and "strong" flash-tube simulations appear in Figure 13. The waveforms for the weak and nominal strength simulations were very similar as compared to the strong flash-tube simulation which exhibited a high-amplitude acceleration response that did not decay appreciably with time. Furthermore, the flash tube did not fail in the strong simulation as progressive distortion of the finite elements in the impact region rapidly decreased the stable time step governed by the Courant condition. Thus, the simulation was terminated at 180 μs. Periodograms are computed for the three cases investigated and are plotted in semi-log form in Figure 14. The simulations involving the weak and nominal flash-tube strengths were nearly identical in the estimate of the power spectral density of the shock signal. However, the energy associated with the impact into the strong flash tube was several orders of magnitude greater and was more uniform in strength across the frequency spectrum; thus, increasing the flash-tube failure strength has the effect of transmitting higher energy modes to the accelerometer. The results indicate that changing the failure strength of the flash tube can substantially modify the temporal and frequency response of the fuze that is subjected to oblique impact.

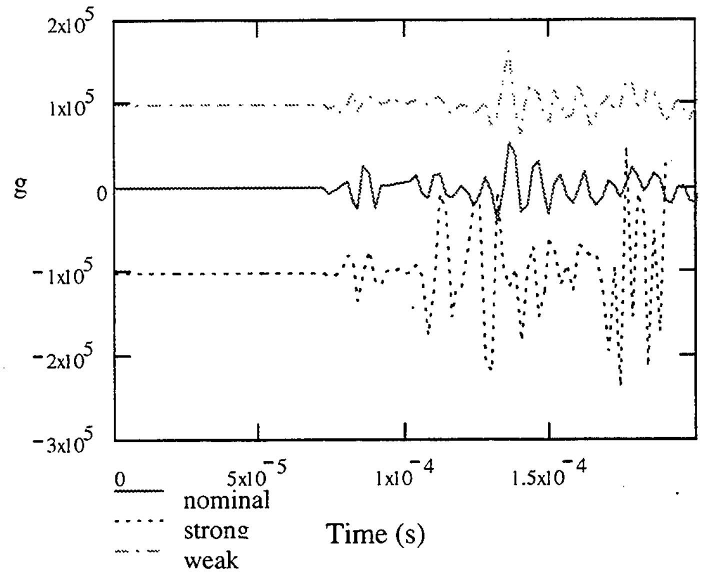

Figure 13. Simulated Accelerometer Response to 200 μs for Weak, Nominal and Strong Flash-Tube Failure Strengths.

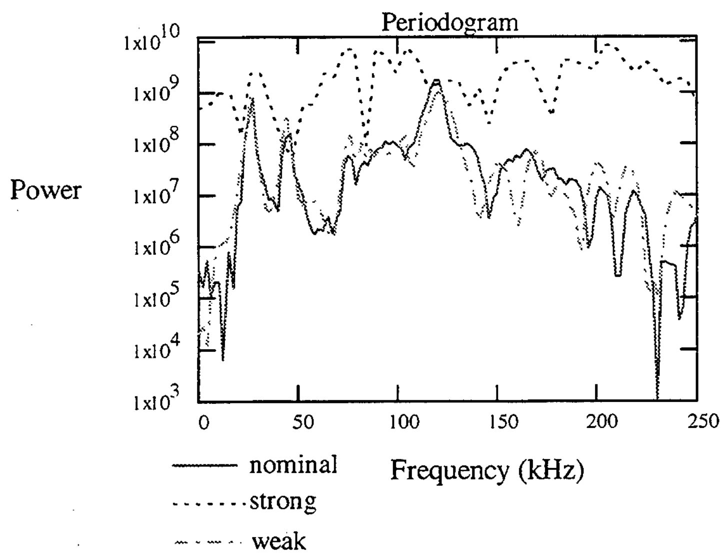

Figure 14. Periodograms for Weak, Nominal and Strong Flash-Tube Simulations (Note Log Scale on Vertical Axis).

4.3 Global Damping. In order to simulate the effect of the UBA's intricate internal structure, the damping coefficient was $\beta = 10^{-8}$ for the computations reported thus far. As the precise effect of this internal structure on the resulting waveform was unknown, the damping

coefficient in the UBA was increased to $\beta = 10^{-6}$ in an effort to further attenuate the 120-kHz energy peak. A comparison of the acceleration histories for the cg of the UBA for the cases $\beta = 10^{-8}$ and $\beta = 10^{-6}$ reveals that increasing the damping coefficient attenuates the resulting waveform (Figure 15). In addition, increasing the damping coefficient to $\beta = 10^{-6}$ attenuates the peak acceleration in the accelerometer to 41 kilo-g. Interestingly, the cg of the UBA contains an energy peak at 30 kHz, but the 120-kHz energy peak is highly attenuated (Figure 16), relative to that predicted in the accelerometer (Figure 10). This observation is independent of the value of β used in the analysis.

Another possible source of the anomalous energy at 120 kHz could be related to spurious frequencies induced by the finite element mesh in the accelerometer. The 0.11-in-thick accelerometer was initially modeled with six hexahedral elements through its thickness resulting in the power spectral density illustrated in Figure 10. Halving the finite element mesh density resulted in attenuation of the energy associated with the spurious frequency at 120 kHz, but the energy at 30 kHz was attenuated as well (Figure 17).

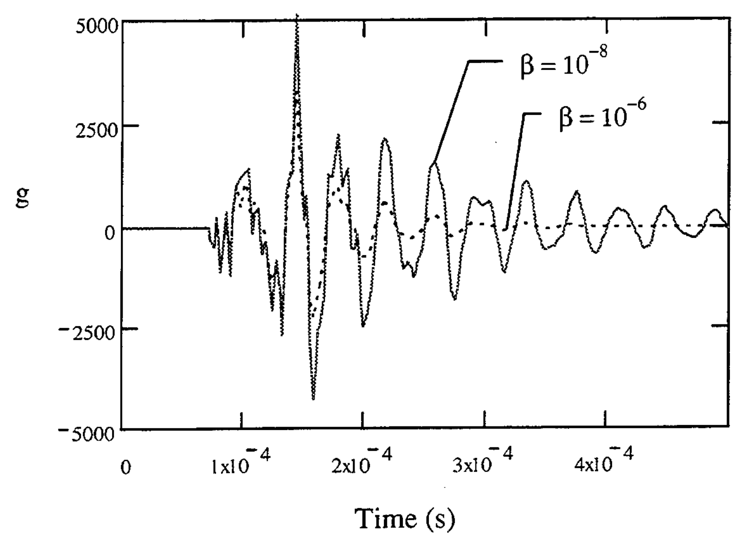

Figure 15. Acceleration Histories for Damping Coefficients $\beta = 10^{-8}$ and $\beta = 10^{-6}$ in the UBA.

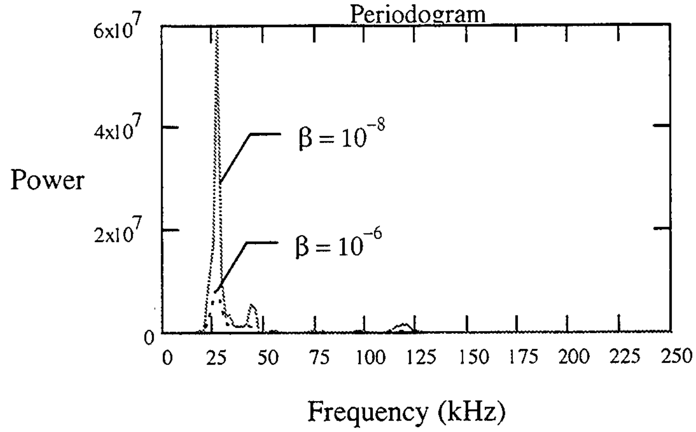

Figure 16. Periodograms Showing UBA Spectral Response With Damping Coefficients $\beta = 10^{-8}$ and $\beta = 10^{-6}$. Note the Relatively Weak Signal Power in the 120-kHz Range.

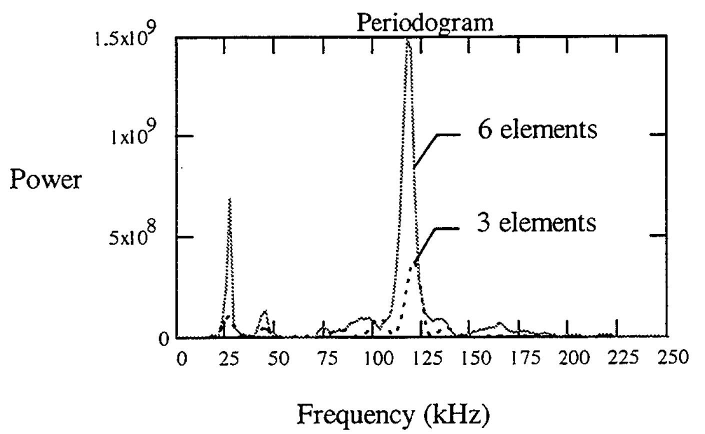

Figure 17. Periodograms Showing Decrease in Power Spectrum in the Accelerometer by Halving the Accelerometer Mesh Density.

5. Discussion and Conclusions

This report outlined the results of a combined experimental and computational study that investigated the transient structural response of the M557 point detonating fuze subjected to low-speed (200 m/s) oblique impact by a hardened-steel projectile. Peak accelerations measured in

the airgun tests averaged 35 kilo-g, whereas peak accelerations predicted by DYNA3D ranged from 40 to 50 kilo-g depending upon the value used for critical damping in the UBA.

A comparison of the estimated spectral response of the simulations and experiments revealed that both contain spectral energy at 30 kHz. Additional tests on fuze simulants whereby the ogive and nose cone were removed from the fuze also contained spectral energy at 30 kHz. This observation indicates that the ogive and nose-cone structural components do not significantly contribute to the frequency content of the observed waveforms. Furthermore, the estimated spectral response at the base of the fuze was shown to be largely dependent upon the failure strength of the flash tube; impact energy is transmitted to the accelerometer as long as the flash tube remains in contact with the UBA. The DYNA3D hydrocode also predicted the presence of a strong spectral peak in the accelerometer at 120 kHz, which was not observed in the impact tests. This spurious spectral peak appears to be an artifact of the finite element analysis as this spectral component is highly attenuated in the cg response of the UBA. How then is energy at this frequency being excited in the model accelerometer?

A final investigation examined the spectral response of a vertical line of nodes along the central axis of the UBA. These axial nodes are a subset of the total number of nodes that comprise the cg response of the UBA. When the nodes that comprise the "spotwelded" failure surface are suddenly released during failure, a high-g stress wave is introduced into the mesh, which attenuates as it travels downward through the UBA. This stress wave excites the axial nodes in the UBA, which contain a dominant spectral energy peak that is phase-shifted in a band around 120 kHz. If the acceleration histories of this subset of nodes are summed and spectrally analyzed, the 120-kHz energy peak attenuates and broadens. The summing procedure is known as signal stacking in the geophysics literature [9] and has the effect of improving the signal-to-noise ratio. As an increasing number of UBA nodes are included in the analysis, the cg response is approached (Figure 16). Why the spectral peaks of axial nodes shift phase in a band around 120 kHz is not known but is currently an area of active study. In real media, however, phase shifts are caused by wave reflections, caustics, and geometrical or material dispersion effects. It is interesting to conjecture that the 120-kHz frequency is related to the fundamental axial mode of vibration of the UBA. Since the height of the UBA is about 0.55 in and the longitudinal wave

speed is 129,816 in/s, this results in a fundamental frequency of about 118 kHz. The 120-kHz energy can be further attenuated with more suitably chosen Rayleigh damping coefficients, or post-processing the finite element transients, which inherently contain spurious frequencies related to multiple wave reflection phenomena and element size effects as discussed in Holmes and Belytschko [10].

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U.S. Army Research Laboratory
ATTN: AMSRL-WM-MB
Aberdeen Proving Ground, MD 21005-5069

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13. ABSTRACT *(Maximum 200 words)*

This report outlines the results of a combined experimental and computational study that investigates the transient structural response of the M557 point detonating fuze subjected to low-speed (200 m/s) oblique impact by a hardened-steel projectile. The problem is of interest to the explosive ordnance disposal (EOD) community as it is a method that is currently used to "render-safe" ordnance and other explosive devices found in the field. An inert M557 fuze is instrumented with a low-mass (1.5 gram) 60-kilo-g uniaxial accelerometer and subjected to oblique impact by launching a 300-gram projectile from a 4-in airgun. The transient structural response of the fuze is compared to the predicted response using the Lagrangian finite element code DYNA3D. Peak accelerations measured in two tests average 35 kilo-g, whereas DYNA3D predicts a 40- to 50-kilo-g peak acceleration depending upon the amount of prescribed damping. Both measured and computed acceleration histories are Fourier-transformed, and the estimated spectral response at the base of the fuze is shown to be dependent upon the failure strength of the flash tube.

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2. Date Report Received ________________________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ________________________________

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